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Influence of synchronized traffic light on the states of bus operating system

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HIGHLIGHTS

- The paper investigates the bus operating system under the control of traffic light.
- The analytical equations for the critical passenger arrival rate and average velocity agree with the simulation results well.
- The average velocity in the free-flow and bunching state oscillates with the increase of T.
- The exact condition for the two states called lag and catch (LC) and variant LC state is presented.
- A monotonic decreasing curve instead of oscillation was observed under nonsynchronous traffic light.

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ABSTRACT

This paper investigates the bus operating system under the synchronized traffic light control strategies with cellular automation. Besides the insufficient capacity, the sufficient capacity is observed in the free-flow state of the phase diagram. An analytical equation for the critical passenger arrival rate is developed. The average velocity of free-flow and bunching state oscillates with the increase of signal period. With the increase of the ratio of green phase time, the oscillation amplitude of average velocity decreases while the oscillation frequency increases. At the same time, the critical passenger arrival rate and each region of the phase diagram also vary synchronously. An analytical equation for the average velocity is developed, which shows good agreement with the simulation results. Two states called lag and catch (LC) and variant LC state are observed. The exact condition for the LC state is presented. Finally, a monotonic decreasing curve instead of oscillation was observed under nonsynchronous traffic light. The results indicate that a proper signal period could improve the efficiency of bus system.

1. Introduction

The public bus plays an important role in urban system. The bus operating system is a typical many-body system which has attracted the interest of a community of physicists and others [1–8]. It was shown that the bus system also exhibits the dynamical phase transition similar to the traffic flow [2].

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However, the bus operating system suffers from the problem of bus bunching, i.e., several buses traveling together. This makes the service inefficient since people need to wait more time. To understand this behavior, many models have been proposed and studied, including cellular automation (CA) models [1,3,4], car-following models [5,6], and time headway models [7,8]. Furthermore, some realistic elements were considered to discuss the bunching problem, such as open boundary [9] and the mixture of buses and cars in a two-lane traffic system [10].

Many strategies such as adjusting the waiting times and cruise speed were proposed to alleviate the bus bunching behavior. Attempting to achieve equal headways, the minimum, maximum and adaptive waiting time method were put forward by Gershenson et al. [11]. Ding et al. proposed the method that buses adjust their speeds adaptively based on the number of passengers waiting at the bus stops [12]. The system performance is improved significantly with this strategy.

The traffic signal is an essential element in urban traffic network. The impact of traffic light has been studied in detail on single road [13], single intersection [14] and urban traffic network [15]. The previous studies mainly concern on the flow of private car. In this paper, the synchronized traffic lights were introduced into the public bus operating system. How does the bus system's states change such as the bunching and phase separation under the control of traffic lights? How to reduce the bunching and improve the system efficiency by traffic light?

The bus system interfered by traffic light has been studied previously by Huang et al. [16]. However, Huang et al. mainly focus on the statistical distributions of time-headway through a mean-field analysis. The dynamical behavior of a single shuttle bus moving between the origin and the destination through one traffic signal has been studied by Nagatani [17]. However only one bus and one signal were considered in the paper. In this paper, a more realistic cellular automata model is developed. We mainly focus on the relationship between the system states or the average velocity and the signal period. The analytical results are also presented which agree with the simulation results well.

This paper is organized as follows. In Section 2, the model is described in detail. The simulation results and discussion are reported in Section 3. Finally, the conclusions are given in Section 4.

2. Model

In this section, a CA model for the bus operating system is presented. As shown in Fig. 1, the buses move on a periodic boundary lattice which is divided into L_{total} cells. Each cell represents a bus stop or a segment of road, which is occupied by at most one bus. It is assumed that there are N_s bus stops and the neighboring bus stops are separated uniformly by L cells. Thus the total number of cells is $L_{total} = (L+1)N_s$. There are N_{light} traffic lights and the neighboring lights are separated uniformly by s bus stops. Thus, $N_s = sN_{light}$. The gap between two neighboring traffic lights actually represents a road section between two intersections in urban road network. In order to simplify, each traffic light is located at the middle of two neighboring stops. Denote i as the number of bus, j the number of bus stop, M the bus capacity and N_b the total number of buses. From $t \to t + 1$, the parallel update rules of the system are as follows.

1. Update of traffic lights:
   The traffic lights are assumed to switching between green and red synchronously. We denote the duration of green phase and red phase, respectively, as T_g and T_r, while $T = T_g + T_r$ denotes the period of traffic lights.
2. Passengers'arrival:
   $N_{ps}(j, t+1) = N_{ps}(j, t)+1$ for each bus stop site with probability λ. Here $N_{ps}(j, t)$ represents the number of passengers waiting at the bus stop j at time t, and λ is the passenger arrival rate.
3. Bus motion:
   (i) If the bus i is not at a bus stop site, there are two cases.
   If the traffic light in front of bus i immediately is red, then $v_i(t + 1) = 0$, $x_i(t + 1) = x_i(t)$. For other cases, $v_i(t + 1) = \min[1, gap_i(t)]$, $x_i(t + 1) = x_i(t) + v_i(t + 1)$. Here $v_i(t)$ and $x_i(t)$ are the velocity and position of bus i at time t, $gap_i\ (t)$ is the gap to the preceding bus $i + 1$.
   Let $N_{pb}(i, t)$ represent the number of passengers on bus i at time t. If $x_i(t + 1)$ is a bus stop site (stop j), then this means that the bus i pulls in the bus stop j at time t+1. In this case, we suppose the number of passengers getting off the bus,
   $$O = \mu \cdot N_{pb}(i, t), \tag{1}$$
   therefore the number of passengers getting on the bus,
   $$I = \min(N_{ps}(j, t + 1), M - (N_{pb}(i, t) - O)). \tag{2}$$
   Thus, the number of passengers on the bus,
   $$N_{pb}(i, t + 1) = N_{pb}(i, t) - O + I, \tag{3}$$
   and the number of passengers waiting at the bus stop j,
   $$N_{ps}(j, t + 1) = N_{ps}(j, t) - I. \tag{4}$$
   The total time that the bus i must stay at the bus stop,
   $$T_{in}(i) = \mathrm{int}[\max(\gamma I, \delta O)] + 1. \tag{5}$$
   Here μ is the proportion of passengers getting off buses. γ and δ are parameters indicating the average time it takes a passenger to get on and off the bus respectively. We take $\gamma > \delta$ to represent the fact that it will take more time getting on than off the bus. In the model, it is assumed that each bus has to stop at every bus stop even if passengers neither get off nor get on it.